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The Effect of Display Size on Disparity Scaling from Differential Perspective and Vergence Cues

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The present study compared the relative effectiveness of differential perspective and vergence angle manipulations in scaling depth from horizontal disparities. When differential perspective and vergence angle were manipulated together (to simulate a range of different viewing distances from 28 cm to infinity), approximately 35% of the scaling required for complete depth constancy was obtained. When manipulated separately the relative influence of each cue depended crucially on the size of the visual display. Differential perspective was only effective when the display size was sufficiently large (i.e., greater than 20 deg) whereas the influence of vergence angle, although evident at each display size, was greatest in the smaller displays. For each display size the independent effects of the two cues were approximately additive. Perceived size (and two-dimensional spacing of elements) was also affected by manipulations of differential perspective and vergence. These results confirm that both differential perspective and vergence are effective in scaling the perceived two-dimensional size of elements and the perceived depth from horizontal disparities. They also show that the effect of the two cues in combination is approximately equal to the sum of their individual effects.

Depth constancy   Depth scaling   Binocular disparity   Differential perspective   Vergence   ®Cue–combination

INTRODUCTION

Horizontal binocular disparities can give rise to a vivid impression of three-dimensional structure. However, the horizontal disparity between two points in the world is insufficient to specify the amount of depth because its magnitude depends crucially on the distance between the observer and the points. For a real object, the horizontal disparity between any pair of points varies roughly inversely with the square of the viewing distance (Kaufman, 1974). Therefore, to determine a depth difference from horizontal disparity (and so achieve depth constancy) it is necessary to incorporate information about the viewing distance.

In theory, an estimate of viewing distance could be provided by either oculomotor cues (Foley, 1980; Cormack, 1984), vertical disparity information (Mayhew & Longuet-Higgins, 1982), or cognitive-pictorial cues such as familiar size or perspective (O'Leary & Wallach, 1980; Predebon, 1993). The purpose of the present paper is to determine the respective contributions of vergence and vertical disparity information in scaling horizontal disparities while keeping all other factors constant. The relative influence of the two cues as a function of display size was also investigated for reasons set out below.

There is strong evidence that manipulating oculomotor information (vergence angle and accommodation) affects the amount of depth perceived from horizontal disparities (Wallach & Zuckerman, 1963; Cumming *et al.*, 1991). Using lenses and a mirror arrangement to manipulate both accommodation and vergence, Wallach and Zuckerman (1963) simulated changes in viewing distance between 66.5 and 133 cm, and found that the perceived depth between the base and apex of a pyramid depicted in their stereogram changed by 75% of the amount required for complete constancy. Cumming *et al.* (1991) reported that the manipulation of vergence angle alone produced 25% of the depth scaling required for complete constancy using an apparently circular cylinder task.

Theoretical considerations show that an estimate of viewing distance is also provided by the vertical disparities present between the left and right eye's images (Longuet-Higgins, 1982; Mayhew & Longuet-Higgins, 1982; Gillam & Lawergren, 1983; Porrill, *et al.*, 1987; Bishop, 1989). Vertical disparity arises because any feature not in the median plane will be closer to one eye than the other and, as a consequence, will project to different vertical positions (and be of different vertical sizes) in the two eyes (Howard, 1970). The binocular vertical size ratio of any object or surface feature is

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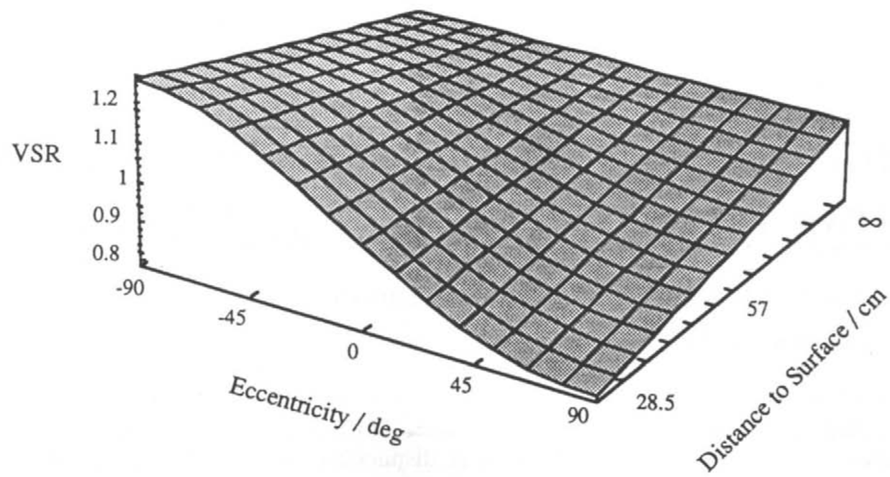

FIGURE 1. The vertical size ratio (VSR) of a feature in the plane of regard varies with both eccentricity and viewing distance. For a fixed distance of the feature from the observer, the vertical size ratio is approximately a sine function reaching maxima at eccentricities of ± 90 deg (elevation = 0).

unaffected by local depth variations (when these are small compared to the absolute distance to the surface) and depends only on the relative distances of the feature from the two eyes. If the angular extent of the feature is small (< 5 deg), then the ratio of the vertical sizes in the left and right images is simply the ratio of the inverse distances to that feature (see Rogers & Bradshaw, 1995a). For a given eccentricity, vertical size ratios decrease with increasing distance and, for a fixed distance, they increase with eccentricity from the median plane as shown in Fig. 1 (see also Gillam & Lawergren, 1983, Fig. 6; Rogers & Bradshaw, 1993).

Empirically, it has been shown that manipulating vertical disparities to simulate different viewing distances affects the amount of depth perceived from horizontal disparities (Rogers & Bradshaw, 1993). They reported that observers perceive around twice as much depth in a sinusoidal corrugation with fixed horizontal disparities at a simulated distance of infinity as compared to a simulated distance of 28 cm. Rogers and Bradshaw (1993) describe the pattern of vertical disparities created when a textured surface is viewed binocularly as differential perspective. This term neatly encapsulates the fact that the pattern of vertical disparities created by the surface is simply the consequence of perspective viewing from two slightly different (eye) positions. Differential perspective will be used as a shorthand for describing this pattern of vertical disparities.

Studies of the effects of oculomotor and differential perspective manipulations on depth scaling, as reviewed above, usually show much less depth scaling than that required for perfect depth constancy. This under-constancy has often been attributed to the shortage of, or conflicts between, different potential depth or distance cues which occur in experiments designed to investigate the influence of one particular cue while other cues are held constant or eliminated (see also Tyler, 1983). Under more naturalistic viewing conditions, where there are many consistent cues to distance, it has been found that depth constancy from horizontal disparities can be much closer to veridical (Glennerster, *et al.*, 1993, 1994). The relative contributions of the different distance cues, however, remain to be determined.

In this paper, we consider the respective contributions of differential perspective and vergence cues to the scaling of horizontal disparities as a function of display size (see also Rogers & Bradshaw, 1995a). The importance of display size arises from the geometrical considerations illustrated in Fig. 1. This shows that the vertical size ratio of any binocular element or feature increases approximately linearly with the eccentricity of the feature from the median plane between 0 and ± 40 deg. Rogers and Bradshaw (1993) suggested that vertical disparities might only be effective when the field of view is sufficiently large (they used 70 × 70 deg fields) since vertical disparities are much larger at these eccentricities. It follows that the failure of previous studies to find an effect of vertical disparity (Cumming *et al.*, 1991; Sobel & Collett, 1991) may have been due to the relatively small size of their stimulus displays (11 and 25 deg, respectively). On the basis of these considerations, we predict an increase in the amount of depth scaling with an increase in display size when changes in viewing distance are signalled by differential perspective alone. On the other hand, there is no reason to expect that the effect of vergence angle manipulations should be influenced by changes in display size. However, when one cue is manipulated independently, the other cue is not eliminated but rather is held constant and appropriate for a particular distance. Hence, if the effect of differential perspective on scaling is greater in larger displays, then a greater conflict is created between the two cues which, in turn, may lessen the effectiveness of the vergence manipulations. If this were the case, the effect of vergence manipulations should decrease with increasing display size. We also sought to establish the amount of depth scaling achieved when both differential perspective

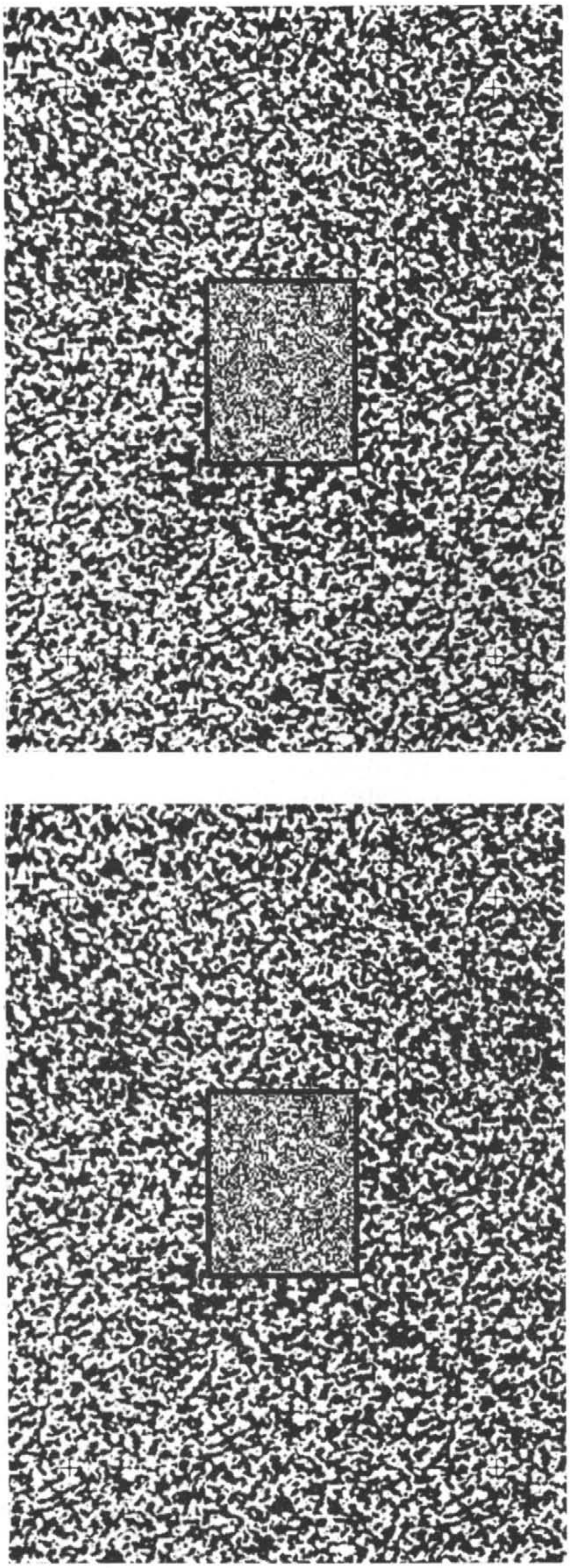

FIGURE 2. An example of the stimuli. These images are untransformed and so when presented in our apparatus, the differential perspective would be consistent for the physical viewing distance of 57 cm. In this case the differential perspective is created by the projection of the stimuli to the eye [see Rogers & Bradshaw (1995a) for examples of the different transformations].

and vergence angle were manipulated together to simulate the same viewing distance.

Rogers and Bradshaw (1995a) outlined four predictions concerning the influence of differential perspective and vergence angle manipulations on the perception of disparity defined surfaces. If either of these cues provides information about absolute distance they predicted that: (1) the test surfaces should appear closer to or farther away from the observer, in accordance with the distance simulated; (2) the perceived two-dimensional size of features and objects should scale in accordance with the distance simulated; (3) the amount of perceived depth from a fixed set of horizontal disparities should vary in accordance with the distance simulated; and (4) the perceived curvature of an extended surface, such as a fronto-parallel plane, should vary in a horizontal direction (parallel to the inter-ocular axis). Predictions (1) and (4) were investigated by Rogers and Bradshaw (1995a) while the present study was designed to address predictions (2) and (3) on size and depth scaling. Observers where asked to make two judgements: (1) the amount of depth between a peak and trough in a sinusoidally corrugated surface defined by a fixed set of horizontal disparities (depth task) and (2) the perceived spacing between the peaks of the corrugations (size task). Both tasks were carried out over a range of simulated viewing distances.

In summary, the present paper investigated whether either perceived depth or perceived two-dimensional size of depth corrugations defined by a fixed set of horizontal disparities was affected when (1) differential perspective, (2) vergence angle and (3) differential perspective *and* vergence angle were manipulated to simulate the viewing of a surface at six different distances (28, 38, 57, 114, 228 cm and infinity). The effects of these manipulations were determined for displays of four different sizes (10, 20, 40 and 80 cm in diameter).

GENERAL METHOD

Stimulus generation

The stereoscopic images were composed of a densely textured "blob-like" pattern (average size of blobs ≈ 2 deg) which surrounded a central 25×20 deg rectangular region filled with random dots (10 min arc). The central region depicted a horizontal sinusoidal corrugation of 0.2 c/deg and 20 min arc peak-to-trough amplitude specified by horizontal disparities (see Fig. 2). The maximum and minimum luminances of the display elements, measured through the mirrors at the position of the eye, were 17.5 and 3.3 cd/m^2, respectively.

Differential perspective and vergence state could be manipulated independently, to simulate different viewing distances. A complete description of the stimulus generation technique is described elsewhere (Rogers & Bradshaw, 1995a) and so only an overview will be given here. Differential perspective can be thought to arise as a consequence of the perspective viewing of a surface from two slightly different (eye) positions. Consider a frontal

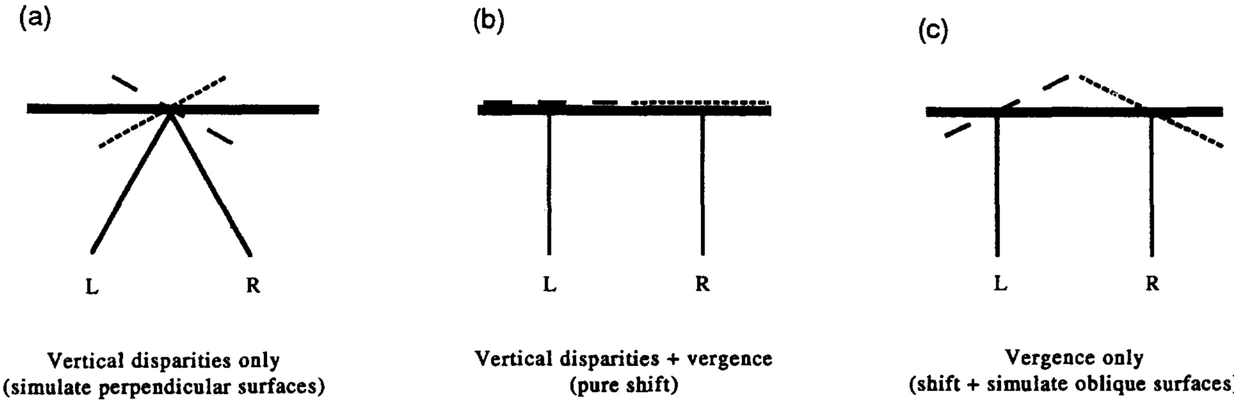

FIGURE 3. Simulating viewing at infinity for (a) differential perspective alone, (b) differential perspective and vergence angle and (c) vergence angle only. The bold, horizontal line represents the display screen and the two dashed lines the relative obliqueness of the surfaces being simulated. The short-dashed line represents the right eye's view and the long-dashed line the left eye's view.

surface. The closer the surface, the more oblique any feature will be relative to the lines of sight from the two eyes. With greater obliqueness, the horizontal gradient of vertical disparities is larger. Therefore to generate the differential perspective that would be created by a real surface at different distances, surfaces at different relative obliqueness to the lines of sight were simulated. For example, to create a stimulus with the same pattern of vertical and horizontal disparities as would be created by a surface at infinity, the original texture was separately transformed to simulate a surface that was perpendicular to the line of sight in each eye [Fig. 3(a)]. Normally when an observer fixates on a surface at 57 cm, a central feature on the surface would be slightly oblique to each of the lines of sight, in fact by + 3.25 deg (half the vergence angle for that distance—assuming no fixation disparities) for one eye and − 3.25 deg for the other. Thus, to simulate a surface lying at infinity (i.e., perpendicular to the lines of sight from the two eyes) while keeping vergence appropriate to 57 cm, the stimulus pattern was transformed by calculating the back-projection of the original texture onto planes rotated through ± 3.25 deg (relative to each eye). When these images were displayed on the projection screens at 57 cm, the image projected to the left eye would be the same as that projected if the original, untransformed stimulus pattern was viewed on screens which were physically perpendicular to the lines of sight from each eye.

To manipulate the differential perspective and vergence cues together, the images projected on the two screens were shifted horizontally. This manipulation has the joint effect of changing the vergence angle *and* the relative obliqueness of the surfaces to the line of sight [Fig. 3(b)]. To manipulate vergence while keeping the differential perspective cue constant, the appropriate horizontal shift was applied and then the image transformed so that the relative obliqueness of the surfaces was appropriate for a viewing distance of 57 cm [Fig. 3(c)].

We refer to the simulated viewing distances by their corresponding vergence angles in min arc: 780, 585, 390, 195, 97.5 and 0 min arc. These vergence angles correspond to simulated viewing distances of 28, 38, 57, 114, 228 cm and infinity, respectively.

Displays of different angular extents were generated by clipping the stimulus pattern with a circular mask prior to stimulus generation. The projected sizes of the images were 10, 20, 40 and 80 cm in diameter which correspond to angular sizes of 10, 20, 39 and 70 deg. Before the pattern was transformed it was blurred by a 3 × 3 Gaussian smoothing function to produce three-step gradients of intensity instead of the sharp luminance boundaries in the original pattern. Sub-pixel shifts in either a horizontal or vertical direction were generated using a standard grey-level interpolation algorithm on the 8-bit greyscale images. Consequently the stimulus appeared slightly blurred. The impression of depth in the central corrugations was smooth and continuous.

Apparatus

Observers sat in a modified Wheatstone stereoscope with two mirrors at precisely ± 45 deg to the median plane and viewed rear-projected images from two Electrohome EDP 58 projection TVs onto two translucent Mylar screens positioned 57 cm from the observer's eyes. (The actual viewing distance of the images was always 57 cm.) When the binocular images were aligned and centred on the appropriate corresponding point on the two screens, the vergence state was set for 57 cm (390 min arc of equivalent vergence). A Macintosh Quadra 950 controlled the stimulus presentation on two Apple video cards with 640 × 480 (horizontal and vertical) pixels refreshed at a rate of 66.7 Hz. Projected pixel size was 10 min arc.

Procedure

For each size of display (10, 20, 40 or 80 cm diameter), the subject was presented with images simulating one of six different viewing distances (28, 38, 57, 114, 228 cm and infinity) specified by either differential perspective, vergence or both cues together. A total of 18 settings (six distances × three cue conditions) were made for each display size in a single session and each session was repeated three times. The order of presentation of the trials in each session was randomized and computer controlled. The observer's task was to estimate (1) the amount of perceived depth in the corrugated surface and (2) the perceived spacing between peaks. Digital callipers were used to make the setting in both cases. These settings were made visually and the spacing between the jaws, in mm, was recorded. The task was self-paced. Three experienced psychophysical observers took part in the experiment.

RESULTS

The amount of depth perceived at each simulated viewing distance—specified by differential perspective, vergence and both cues together—is plotted in Fig. 4. The dashed lines depict how perceived depth, from a fixed horizontal disparity, should vary with viewing distance if perfect depth constancy was achieved. This was based on the relationship

$$\text{disparity} = \frac{Id}{D(D-d)} \tag{1}$$

where the peak-to-trough disparity is in radians (in this case, the equivalent of 20 min arc), I is the inter-ocular separation (cm), d is the depth difference (cm), and D is the observation distance (cm). Equation (1) is based on a definition of disparity as being the difference of two symmetric vergence angles and uses the small angle approximation in which the tangent of the angle is assumed to be equal to the angle in radians (see Howard & Rogers, 1995). Since d is usually small by comparison to D we get

$$\text{disparity} \approx \frac{Id}{D^2}. \tag{2}$$

This expression indicates the approximate inverse squared relationship between the disparity of an object and its distance from the observer, as described in the Introduction.

Figure 4 shows that manipulations of vergence angle and differential perspective both affect the amount of perceived depth from horizontal disparities. In each case there is an approximate monotonic relationship between the amount of perceived depth and the simulated observation distance. As the simulated distance was increased, perceived depth also increased although the magnitude of the effect was less than that predicted by equation (1).

To quantify the magnitude of the depth scaling, the perceived depth was transformed into an "effective scaling distance" (see Foley, 1980). This was calculated using equation (1) with $I = 6.5$ cm, a disparity of 20 min arc (in radians) and d the perceived depth measured in the experiment. Each effective scaling distance was then expressed as an equivalent vergence angle and the data replotted in Fig. 5. The magnitude of depth scaling for a particular cue can be quantified by determining the slope of the best fitting straight line. The dashed line with a slope of 1 depicts perfect scaling.

Figure 5 shows that the relationship between "effective scaling vergence angle" and "simulated vergence angle" is approximately linear although the slopes of each function are considerably less than 1 (perfect scaling). In each graph the functions cross perfect scaling (dashed 45 deg line) close to a simulated vergence angle of 390 min arc (57 cm) which was the actual observation distance used in the experiment. Here, all distance cues including accommodation were consistent and appropriate.

The increasing influence of differential perspective on depth judgements can be clearly seen with the increasing size of the display. With displays of 80 cm in diameter, the independent manipulation of differential perspective (keeping vergence angle constant) produced a slope of 0.15 (15% of complete depth constancy), whereas in the smallest size of display the effect of differential perspective was negligible (< 1%). Vergence manipulations were effective at all display sizes but in this case their effect decreased as field size was increased (34 to 19% when the display was increased from 10 to 80 cm diameter). This may suggest that vergence is a less effective cue with larger displays but it is more likely that the effect is due to the increasing influence of the (conflicting) differential perspective information in the larger displays. (Note that when vergence angle or differential perspective was manipulated independently, the other cue remained constant and appropriate to the actual viewing distance of 57 cm.) With 10 deg displays the influence of vergence manipulations was similar in magnitude to that reported by Cumming *et al.* (1991) who used similar sized stimuli (11 deg). When both cues were manipulated together, the magnitudes of depth scaling were similar (≈ 34%) across all different display sizes.

Although the magnitude of the effects were substantial, they remain well short of that required for complete depth constancy and possible reasons for this are considered in the Discussion. The amount of depth scaling expressed as a percentage of that required for complete depth constancy for each condition is shown in Fig. 6.

Note that for each display size the effects of vergence and differential perspective cues appear to be roughly additive: the percentage constancy for both cues manipulated together approximately equalled the sum of their individual effects. This relationship holds despite the fact that their respective contributions changed markedly with changes in display size. One interpretation of this additivity, although we did not test it formally, is that the visual system combines the information from both cues, with a different weighting given to each, in a type of pooling strategy (see Landy *et al.*, 1995). In this

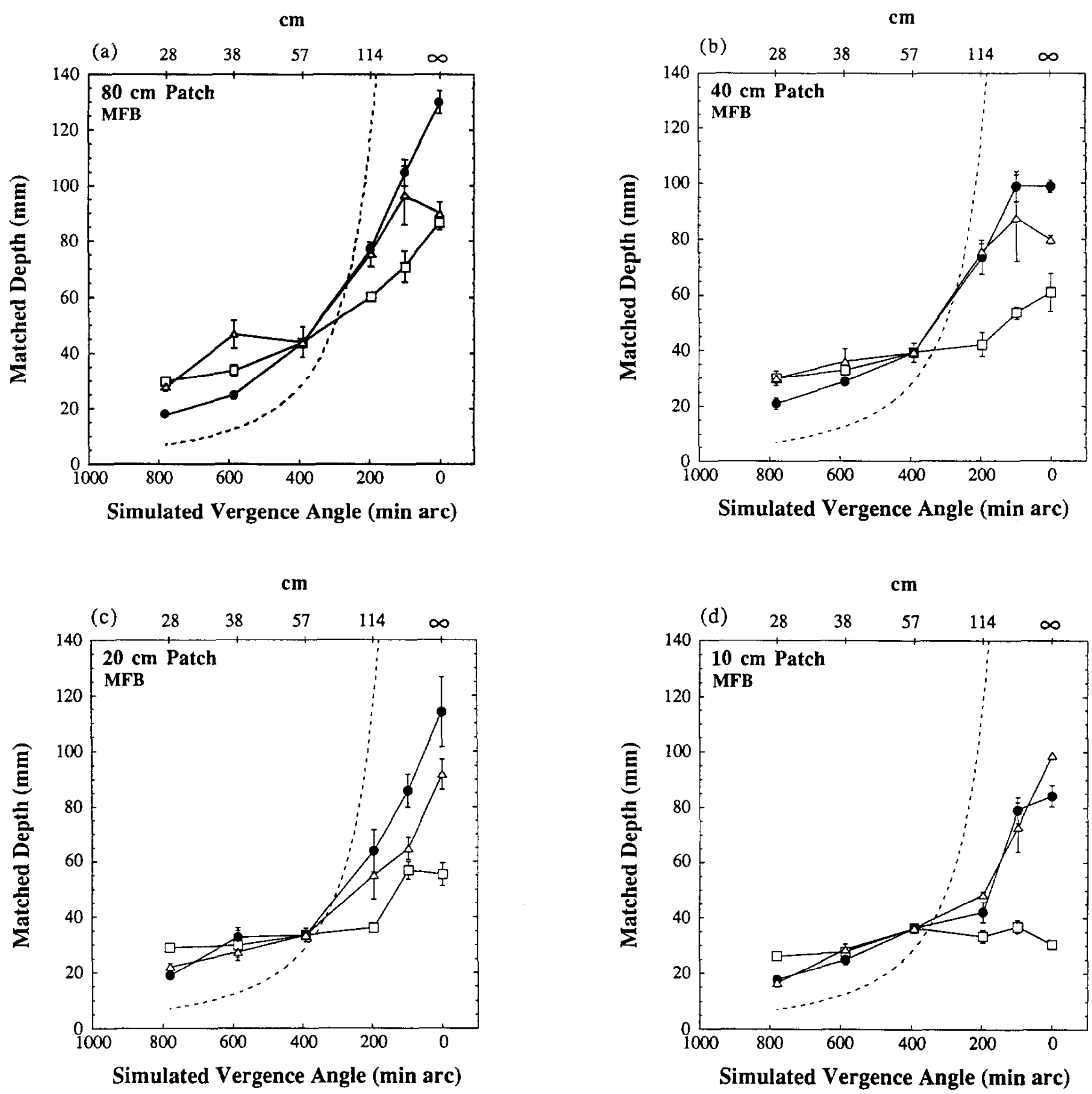

FIGURE 4. Depth settings for one observer (MFB). The manipulation of differential perspective and vergence together is depicted by ●, vergence alone by △ and differential perspective alone by □. The dashed line depicts the amount of depth that would be perceived if complete depth constancy was achieved [based on a rearranged form of equation (1)]. Each point is the mean of three settings in each condition at each field size. The ordinate in each graph indicates matched depth in mm and the abscissa indicates the simulated vergence angle. The simulated distance in cm is shown above each plot for convenience. Results for the 80 cm condition are shown in (a), the 40 cm condition in (b), the 20 cm condition in (c) and the 10 cm condition in (d). Each of the three observers produced a very similar pattern of results.

type of scheme the weights given to each cue would change as a function of display size.

The results described so far show that manipulations of vergence angle and differential perspective influence the amount of depth perceived from a fixed set of horizontal disparities.

The theoretical considerations described in the Introduction suggest that perceived two-dimensional size should also be affected by manipulations of differential perspective and vergence angle. Retinal disparity and retinal size both co-vary with viewing distance but their respective relationship to distance differs. For a given physical object, retinal disparity between any pair of points decreases in proportion to the distance squared (to a first approximation), whereas retinal size of the object decreases in proportion to distance.

Observers were also required to make a size judgement about the perceived two-dimensional separation between the peaks of the corrugations depicted in the stimuli. The ○ in Fig. 7 show that these separation judgements increased monotonically with increases in simulated viewing distance. Also shown in Fig. 7 are the the depth judgements for this condition (●). If we take the different relationships that disparity and two-dimensional size have with viewing distance into account, then depth and separation judgements can be compared to establish whether a similar estimate of viewing distance was used

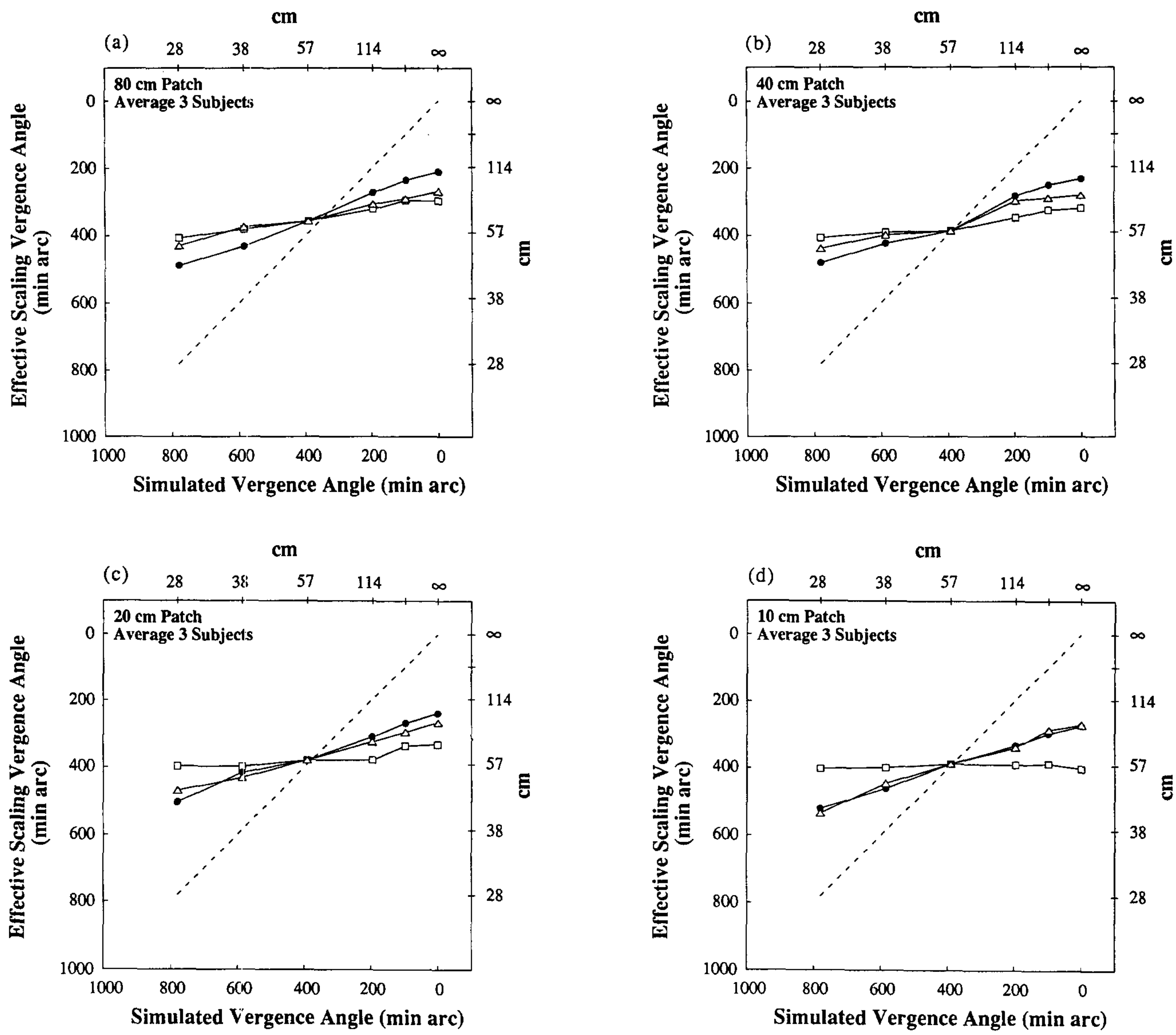

FIGURE 5. The average depth settings of the three observers expressed as effective scaling vergence angle (see text). The ordinate indicates the effective scaling vergence angle and the abscissa indicates the simulated distance expressed as a vergence angle. The equivalent distances in cm are given on the alternative axes. Differential perspective and vergence together is depicted by ●, vergence alone by △ and differential perspective alone by □. The dashed line indicates the amount of depth that would be perceived if complete depth constancy was achieved. The SEs of the slopes taken from the best-fitting regression lines for each observer were less than 3% in all conditions (error bars are shown in Fig. 6).

in the scaling of disparities and in the scaling of two-dimensional sizes. The dashed line plots the ratio of

$$\frac{(\text{separation})^2}{\text{depth}}$$

If the same estimated observation distance was used for both judgements then this line should be horizontal. This relationship holds reasonably well over the entire range of simulated distances between 28 cm and infinity.

DISCUSSION

The results reported here show that when either the vergence state or the differential perspective cue was manipulated to simulate different viewing distances, both the perceived depth and the perceived two-dimensional size of a fixed corrugated surface were affected. Moreover, we have shown that the effectiveness of vergence angle and differential perspective is crucially dependent on display size.

When differential perspective was used to simulate different observation distances while vergence angle was kept constant, approximately three times as much depth was perceived at a simulated distance of infinity compared to a simulated distance of 28 cm in a large 80 cm (70 deg) display. This ratio of 3:1 is similar to that reported by Rogers and Bradshaw (1993), who used the same range of simulated viewing distances. The influence of differential perspective was negligible with the smaller 10 cm displays, as might be expected given the smaller magnitude of the differential perspective cue for displays

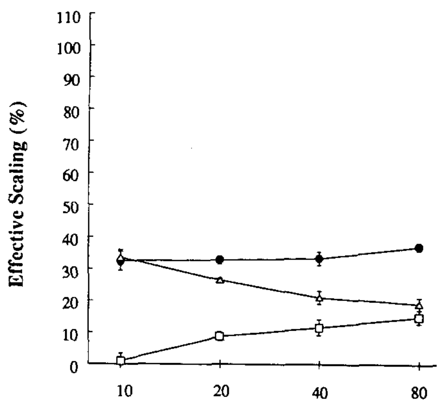

FIGURE 6. The percentage depth constancy obtained in each condition is shown for differential perspective and vergence (●), differential perspective only (□) and vergence only (△). The ordinate shows the percentage depth constancy and the abscissa the display size. The error bars are the SEs of the estimates of effective scaling determined for the three subjects (i.e., the slopes from Fig. 5).

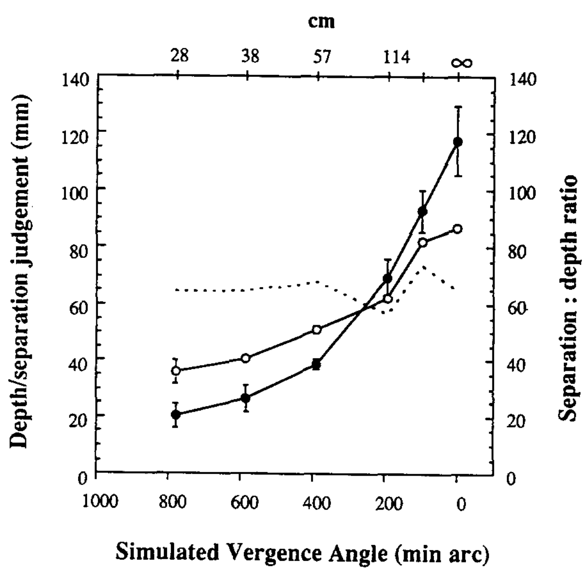

FIGURE 7. The depth and two-dimensional separation judgements made in the differential perspective *and* vergence condition are shown for the 80 cm display size. These data are representative of the other display sizes. ● show depth judgements and ○ show separation judgements. The dashed line plots the result of dividing the square of the separation judgements by the depth. The abscissa indicates the simulated vergence angle and the ordinate the depth or separation judgement in mm. If the amount of scaling for both tasks is similar, then the ratio of the separation: depth judgements should result in a horizontal line.

of this size (Fig. 1). This suggests that the vertical size ratios created by features in the display eccentric to the median plane are important in making these judgements. In the present study, observers were encouraged to move their eyes around the display and so it cannot be concluded that the larger binocular size ratios present in the more eccentric parts of the display were necessarily detected by more peripheral regions of the retina. Hence the question of whether the vertical size ratios stimulating the peripheral retina can affect perceived depth directly, or whether eye movements are required to bring eccentric parts of the display into central vision, cannot be answered by the present experiment. Rogers, Bradshaw and Glennerster (1994), however, addressed this issue directly. They determined the sensitivity functions for vertical disparity manipulations for a task in which observers were required to judge the curvature of a surface (convex/concave) relative to flat and fronto-parallel under two different conditions. In the first, observers were required to fixate a central position whereas in the second, observers were able to move their eyes freely. Sensitivity to the vertical disparity manipulations was found to be similar in the two conditions. Therefore it seems likely that vertical disparities stimulating the peripheral retina, created by the larger displays, can affect perceived depth directly and that eye movements to bring these disparities into foveal vision are not essential.

With large 80 cm displays (70 deg), approximately four times as much depth was perceived at a simulated distance of infinity than at a simulated distance of 28 cm, when vergence angle was manipulated independently and vertical disparities were held constant. The influence of vergence angle decreased for the larger display sizes where, as we noted above, the influence of (conflicting) differential perspective information was increased. When both vergence and differential perspective were manipulated together, nearly eight times more depth was perceived at a simulated distance of infinity than at a simulated distance of 28 cm. Thus the magnitudes of the depth scaling effects were substantial in each condition even though they fell short of that required for complete scaling. The percentage constancy from the manipulation of differential perspective alone, vergence angle alone or both cues together, was 15, 19 and 37%, respectively for the 80 cm diameter displays.

One reason for the under-constancy in all three conditions may be the conflicting distance information from other cues that were also present in the stimuli. For example, texture size, the overall size of the patterns and accommodation all remained constant, and indicated that the stimulus was positioned at a fixed distance from the observer. In more naturalistic conditions, however, when virtually all cues to distance, including familiar size, are consistent and appropriate for a particular observation distance, depth constancy from disparity information has been found to be close to perfect (Glennerster *et al.*, 1993, 1994). They found that the extent of depth constancy varied between 75 and 100%, depending on the observer's task.

Disparity scaling may be achieved by first obtaining an estimate of the viewing distance and then using it to scale the horizontal disparities in order to calculate depth (see Foley, 1980; Bishop, 1989). There is evidence to suggest that scaling was accomplished in this way in the present experiment, since subjective reports made by the observers indicated that perceived distance to the surface (and perceived size of the texture elements) also changed with changes in the simulated observation distance. This was particularly apparent when vergence angle was manipulated but it was also found when differential perspective was manipulated independently (see also Rogers & Bradshaw, 1995a, Appendix 1). Moreover, when the different relationships that disparity and two-dimensional size have with viewing distance were taken into account ($1/D^2$ and $1/D$, respectively), we found that both were scaled to the same extent (see Fig. 7). This suggests that the same estimate of viewing distance was used for both disparity and size scaling. Rogers and Bradshaw (1995b) have investigated this issue further. They compared the amount of size, depth and shape scaling and found that judgements of two-dimensional size, of depth, and of shape were scaled to a similar extent when different viewing distances were simulated by a combination of vergence and vertical disparities. Paradoxically, the judgements of absolute distance produced a much greater range of estimates than those derived from the two-dimensional size, depth and shape tasks which suggests that the estimate of D used for scaling may not be related to the actual perceived distance to the stimulus in a simple way.

In certain situations, however, the characteristics of stereoscopic surfaces may be determined without an explicit estimate of viewing distance. For example to judge successfully whether a surface is flat and fronto-parallel Rogers and Bradshaw (1995a) speculated that an explicit computation of viewing distance might not be required. Instead they identified an invariant property in the vertical/horizontal disparity field to which the visual system might be sensitive: if the horizontal size ratio of a small surface feature in the two eyes equals the square of its vertical size ratio then the patch must lie in a frontal plane, irrespective of its distance from the observer. If the visual system could take advantage of this invariant property then veridical frontal plane judgements could be made without explicit knowledge of the viewing distance. Using a similar experimental design to the one reported here Rogers and Bradshaw (1995a) found the magnitude of scaling in a frontal plane task was close to 100% when both differential perspective and vergence angle cues were manipulated. In the frontal plane task observers were required to adjust the pattern of horizontal disparities until the surface appeared to be flat and lie in a fronto-parallel plane. Their results are summarized in Fig. 8.

The existence of this invariant property may go some way to explain the different magnitudes of frontal plane scaling reported by Rogers and Bradshaw (1995a) and the depth scaling found in the present study (cf. Figs 6 and 8). Whereas the depth judgement used here requires an explicit calculation of viewing distance, frontal plane judgements do not. In addition, it may account for the fact that the differential perspective cue was effective in making frontal plane judgements with the 10 deg displays, whereas its influence was negligible in 10 deg displays in the present experiment. However, the use of this ratio cannot account for the fact that frontal plane

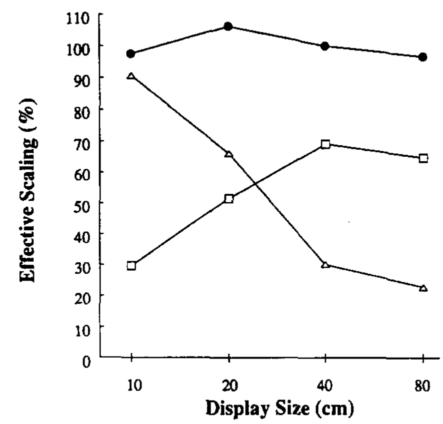

FIGURE 8. The extent of constancy from Rogers and Bradshaw (1995a), using a similar experimental design but a frontal plane task. The ordinate indicates percentage depth constancy of that required for complete scaling and the abscissa display size. Plot symbols are the same as before (see Fig. 4). The amount of depth scaling for this task is considerably more than found in the present experiment, being close to 100% when both vertical disparity and vergence are manipulated together.

scaling was also greater in Rogers and Bradshaw's (1995a) experiment when vergence angle was manipulated alone. There were other differences between the two experiments which also may have contributed to the difference in the magnitude of the scaling, such as the nature of the stimuli differed. There is a statistical contingency between the range of horizontal disparities and viewing distance—disparities from near objects are generally larger. If the visual system exploited this contingency then a surface with 20 min arc disparity at a simulated distance far from the observer would constitute an unlikely real-world situation. This may have created a further source of conflict which limited depth constancy. This was not the case in the frontal plane experiment where the simulated range of horizontal and vertical disparities in the fronto-parallel surfaces at each of the simulated distances did not differ substantially from those which occur naturally.

When differential perspective and vergence angle were manipulated together and each signalled the same viewing distance, depth constancy remained reasonably constant at around 35% for all display sizes. However, the relative influence of the cues when one was manipulated to simulate a particular observation distance, and the other was held constant, differed markedly and depended on the size of the display. The approximate additivity between the cues suggests that the respective estimates of viewing distance from differential perspective and vergence cues are weighted by the visual system according to some criteria which depend on display size before they are combined. This is consistent with models of sensor integration which characterise cue-combination as a weighted linear summation or weak fusion (Bülthoff & Mallot, 1988; Maloney & Landy, 1989; Landy *et al.*, 1995).

In conclusion, we have demonstrated that the manipulation of vergence angle and differential perspective cues, both separately and in combination, affect the perceived depth and perceived two-dimensional size of disparity defined surfaces. The magnitudes of the separate effects were approximately additive and were found to vary as a function of the size of the display. However, although the magnitudes of the effects are substantial, they are still well short of that required for complete depth constancy. The various sources of cue-conflict in the stimuli are the most likely cause of this under-constancy.

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